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Search for gamma-rays above 10 TeV from Markarian 421 in a high state with the CANGAROO-II telescope

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Abstract. A preliminary result from Markarian 421 observations in the energy region above 10 TeV with the CANGAROO-II 10 m telescope is presented. In January 2001, the HEGRA group reported that Markarian 421 had become very active, with flux levels up to 4 times that of the Crab Nebula. As a result, we observed Mkn 421 during six nights from January 24th to February 1st, and four nights from March 1st to 4th. Observations were carried out using the very large zenith angle technique (∼70 degree) and the energy threshold is estimated from Monte Carlo simulations to be around 10 TeV. We have detected gamma-ray emission in this energy range.

1 Introduction

Markarian 421 (Mkn 421, z=0.031) was the first extra-galactic source from which TeV gamma-ray emission was detected (Punch et al., 1992). Extensive measurements of the gamma-ray flux in the TeV energy region have been carried out by several groups using the ground-based imaging Čerenkov telescope (Krennrich et al., 1999; Aharonian et al., 1999; Piron et al., 2001). The energy spectrum up to 10 TeV has been measured by observations at large zenith angles, up to 60 degrees, and can be well described by a power law with a spectral index $-2.5\sim -3.0$.

It is generally believed that TeV gamma-rays from extra-galactic sources will suffer from the absorption due to photon-photon collisions with inter-galactic infrared radiation (Gould & Schrèder et al., 1967; Stecker, de Jager & Salamon, 1992). However, at present, no cutoff due to this absorption has been detected in the Mkn 421 spectrum. In order to determine meaningful constraints on this expected cutoff, it is important to extend measurements of the spectrum to energies above 10 TeV.

In this paper, a preliminary result from Mkn 421 observations with the CANGAROO-II 10 m telescope is presented. We observed this target at very large zenith angles of about 70 degree and searched for gamma-rays above 10 TeV. A

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Date	MJD start	obs. time (hr.)
24-Jan-2001	51933.7041	1.1
26-Jan-2001	51935.7052	1.2
27-Jan-2001	51936.7050	1.6
30-Jan-2001	51939.6737	2.1
31-Jan-2001	51940.6737	2.1
1-Feb-2001	51941.6777	1.9
1-Mar-2001	51969.6381	0.9
2-Mar-2001	51970.6346	1.2
3-Mar-2001	51971.6144	1.6
4-Mar-2001	51972.6549	0.7

Table 1. Date, modified Julian day and effective observation hours for Markarian 421 observations.

Monte Carlo study of this observation mode is also described.

2 Observation of Mkn 421

The CANGAROO-II telescope is located near Woomera, South Australia (136°47′E, 31°06′S). A detailed explanation of the CANGAROO-II telescope is given elsewhere (Tanimori et al., 1999; Mori et al., 1999, 2000, 2001; Kubo et al., 2000; Kawachi et al., 2001).

The telescope was pointed in the direction of Mkn421 for six nights from January 24th to February 1st, during which two nights were lost due to bad weather, and four nights from March 1st to 4th in 2001. Information about these observing periods is summarized in Table 2. Mkn 421 was in a high state during these observation periods. In the first period, the TeV activity was monitored night by night by the HEGRA group (HEGRA , http://www-hegra.desy.de/mrk-421/). Their preliminary result shows that flux lies in the range of 1∼4 times that of the Crab Nebula. Although there was no HEGRA measurement in the second period, Mkn 421 was still in a high state according to the X-ray measurements of the RXTE/ASM group (RXTE/ASM , http://xte.mit.edu/ASM_lc.html).

Mkn 421 was observed at zenith angles of ∼70 degrees as the elevation angle in culmination is 20.7 degrees at the site of CANGAROO-II telescope. Observations were scheduled when the source was above an elevation angle of 18 degrees. The observable time amounts to about two and a half hours per night. Data were taken on moonless and clear nights. An OFF source run, displaced in right ascension, followed or preceded the ON source run. An event trigger was registered when $3 \sim 5$ individual pixels exceeded a threshold of about 3 photoelectrons, depending on the night sky background.

3 Analysis method

The ADC and TDC information recorded for individual tubes are calibrated with the events triggered with a blue LED flasher before each observation. Flat fielding of the photomultipliers' gains and correction of TDC slewing effect are carried out using this data. Camera pixels triggered by sky noise are eliminated by the following procedure of image cleaning. Pixels with pulse heights greater than ∼3.3 photoelectron, triggering within 30 nanoseconds of the timing center of the event and with more than three neighboring hit pixels are used. Final acceptance requires more than five hit pixels in each event.

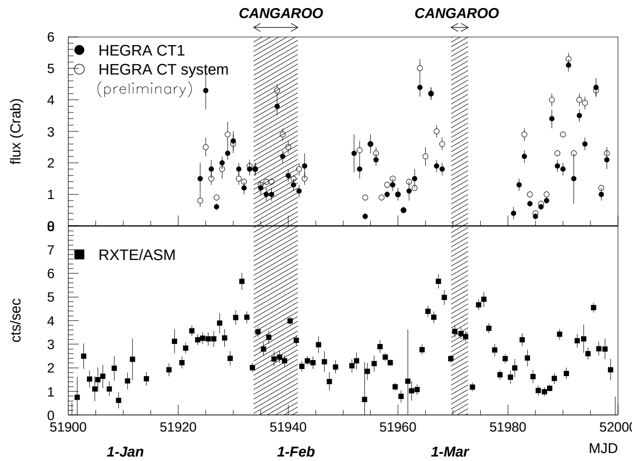

Fig. 1. TeV and X-ray activity measured by the HEGRA and RXTE/ASM groups, from (HEGRA , http://www-hegra.desy.de/mrk-421/) and (RXTE/ASM , http://xte.mit.edu/ASM_lc.html). The one-day averaged data is shown for lightcurve by RXTE/ASM. The observation period of the CANGAROO-II telescope is shown by the hatched region.

In order to reject data affected by cloud etc., data for this analysis were selected based on the following criteria: Data recorded under good sky conditions are used; The elevation angle of Mkn 421 was above 18.5 degrees; and data, which event rate after the image cleaning procedure is less than by 2 r.m.s. from the averaged rate of the whole data, are eliminated. This cut does not exclude any reasonable short-term gamma-ray flare.

As a result, observations totalling 14 hours for ON source and 13 hours for OFF source were selected. The average elevation angle of the selected data is 20.2 degree and its r.m.s. is 0.6 degree, thus data which is taken around culmination are selected.

The selection of gamma-ray events is based on the standard imaging analysis parameters; "Width", "Length", "Distance" and "Alpha" (Hillas, 1982). In this analysis, we adopted the Likelihood method (Enomoto et al., 2001) for the selection of gamma-ray events, instead of the conventional parameterization method. The discrimination of gamma-ray events is based on the probability ratio R_{prob}, expressed as follows :

$$R_{prob} = \frac{Prob(\gamma)}{Prob(\gamma) + Prob(B.G.)}$$

where $Prob(\gamma)$ and $Prob(B.G.)$ are calculated probabilities of image shape parameters for gamma-ray and background events, respectively. These are the products of individual probabilities for "Width", "Length" and "Distance", which

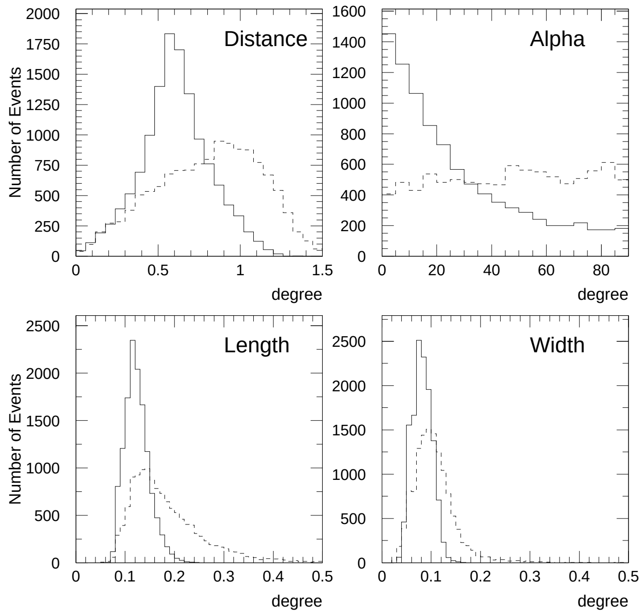

Fig. 2. Shower parameter distribution of gamma-ray Monte Carlo simulation (solid line) and background (dashed line). The "Alpha" distribution is obtained for selected events by the cut of image parameters.

are derived from the functionized distribution using gamma-ray simulations and and OFF source events. Energy dependence is taken into account in these probability functions. We adopted a cut of 0.56, as the signal-to-noise (S/N) ratio was maximized at this value in the study using simulated gamma-rays and background events.

4 Monte Carlo simulation

We have carried out a Monte Carlo simulation of the development of electro-magnetic shower cascade, generation and attenuation of Čerenkov photons, reflection of photons at the mirror surface and simulation of electrical hardware. GEANT simulation code (CERN, 1994) is used for the framework of particle tracking. Photon attenuation in the atmosphere, mirror reflectivity, and quantum efficiency of photomultipliers are included as a function of Čerenkov photon wavelength. The measured point spread function and mirror reflectivity is used. Performance of ADC and TDC electronics is also simulated, including accidental hits due to sky noise.

Gamma-ray events are generated in the energy range of 3$\sim$50 TeV with the assumed spectrum of $E^{-3.0}$. The elevation angle of each event is adjusted according to the distribution of selected data so as to reduce the difference in energy scale between real data and simulation, since the energy scale is very sensitive for large zenith angle observations.

Fig 2 shows the parameter distributions obtained from gamma-ray simulations and OFF source events. For observations at large zenith angle, the shower development point is relatively farther from the telescope due to the thicker atmosphere. This implies a higher energy threshold with a broader effective area (Sommers & Elbert, 1987; Tanimori et al., 1994, 1998). The shower images focused on camera plane become smaller and the location of images moves closer to the target direction. The parameter values become smaller, compared with those of the observation near zenith, due to these effects. The resolution of the pointing angle, "Alpha", also decreases, but is still usable. Naturally the signal-to-noise ratio is smaller than for higher elevation observations, but not so small that it is impossible to discriminate against cosmic-ray protons.

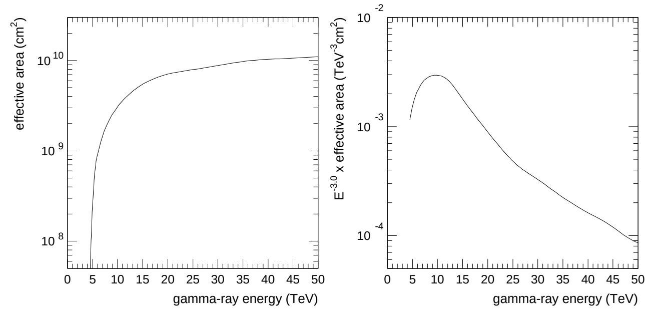

Fig. 3. Effective area (left) and its product with $E^{-3.0}$ spectrum (right). The energy threshold is estimated to be around 9.3 TeV, which is defined as the maximal point of this distribution.

Fig 3 shows the effective area and relative event rate for gamma-rays, which is the product of the effective area times the assumed spectrum of $E^{-3.0}$. The energy threshold is defined where the event rate becomes maximal and estimated to be 9.3 TeV. The averaged effective area above this energy threshold is calculated to be 5×10^9 cm^2. It increases to 10^{10} cm^2 as the gamma-ray energy increases.

5 Result and discussion

Fig 4 shows the distribution of the image orientation angle "Alpha". The normalization factor between ON and OFF observations is obtained from the number of events in the "Alpha" distributions between 40° and 90°. The gamma-ray signal region is alpha $<$ 20 degrees, and the excess events after subtraction of the background is 221 $\pm$ 39 events, corresponding to a significance of 5.6 σ. The broader alpha acceptance is due to the shrinkage of the shower images as predicted from gamma-ray simulations at very large zenith angles.

This preliminary result implies the detection of gamma-rays from Mkn 421 in the energy region of 10$\sim$50 TeV. A refined analysis will be important for studies of the infrared radiation absorption, as discussed in section 1. Furthermore, we have demonstrated that there is sensitivity for the higher energy region above 10 TeV from the study of Monte Carlo simulation. Further analysis may enable constraints to be placed on the intergalactic infra-red background.

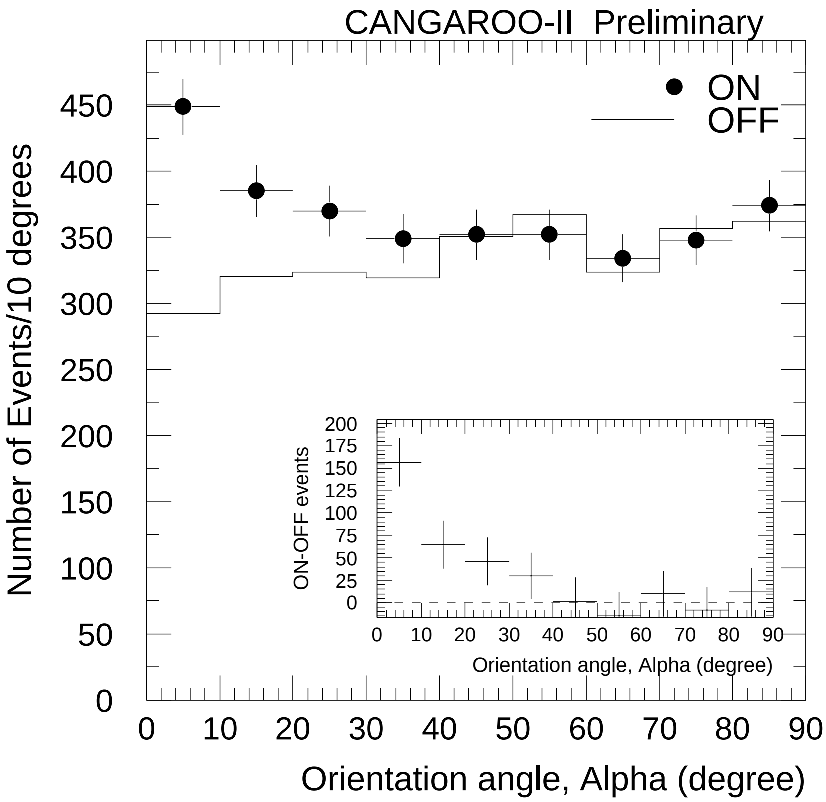

Fig. 4. Image orientation angle "Alpha" distribution of Markarian 421 observed by CANGAROO-II 10 meter telescope. Dots with error bars are ON source data and the solid line is for the OFF source data. The background-subtracted distribution is shown in the inserted graph.

6 Conclusion

We have observed Markarian 421 with the CANGAROO-II 10 m telescope for 14 hours (ON source data after cuts) while the source was in a high state at both X-ray and TeV energies around the end of January and the beginning of March, 2001. The observations were carried out at very large zenith angles, around 70 degrees. The viability of gamma-ray observations are verified with Monte Carlo simulations. The energy threshold and effective area are estimated to be 9.3 TeV and 5×10^9 cm^2, respectively. An excess of 221 ± 39 events was found using Likelihood method. This corresponds to a significance of 5.6 σ and the preliminary detection of gamma-rays in the energy range of 10$\sim$50 TeV.

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References

Aharonian, F.A. et al. A&A, 350, 757, 1999.
CERN Program Library Long Writeup W5013, 1994.
Enomoto, R. et al., to appear in Astropart. Phys., 2001.
Gould, R.J. & Schrèder G. Phys. Rev., 155, 1408, 1967.
Hillas, A.M., J.Phys. G, 8, 1475, 1982.
Kawachi, A. et al., Astropart. Phys. 14, 261, 2001.
Krennrich, F. et al. ApJ, 511, 149, 1999.
Kubo, H. et al., in Proc. GeV-TeV Gamma-ray Astrophysics Workshop (August 13-16, 1999, Snowbird, USA; AIP Conf. Proc. 313), p.313, 2000.
Piron, F. et al. A&A, in press
Mori, M. et al., in Proc. 26th ICRC (August 17-25,1999, Salt Lake City, USA), Vol.5, p.287, 1999.
Mori, M. et al., in Proc. GeV-TeV Gamma-ray Astrophysics Workshop (August 13-16, 1999, Snowbird, USA; AIP Conf. Proc. 515), p.485, 2000.
Mori, M. et al. In these proceedings, 2001.
Punch, M. et al. Nature, 358, 477, 1992.
Sommers, P. and Elbert, J.W. J. Phys. G:Nucl. Phys. 13, 553, 1987.
Stecher, F.W., De Jager, O.C., Salamon, M.H., ApJ, 390, L49, 1992.
Tanimori, T. et al., ApJ, 429, L61, 1994.
Tanimori, T. et al., ApJ, 492, L33, 1998.
Tanimori, T. et al., in Proc. 26th ICRC (August 17-25,1999, Salt Lake City, USA), Vol.5, p.203, 1999.